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AFRPL-TR-69-234

U-4746

November 1969

EVALUATION OF INFILTRATED TUNGSTEN NOZZLE INSERTS

Prepared For:

Department of the Air Force
Headquarters, Air Flight Test Center
(AFTC) Edwards Air Force Base, California

Under Contract: F04611-69-C-0039

Prepared by:

W. H. Armour
J. G. Baetz
J. K. Lewis
R. E. Marcus

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SECTION I

INTRODUCTION

In December 1968 Philco Ford commenced on a contract with the Air Force Rocket Propulsion Laboratory (AFRPL) to conduct a multiphase program. In addition to the design, material selection and fabrication of rocket nozzles for high pressure testing and additional nozzles for multiple restart testing, an effort was undertaken to test six Government furnished nozzles assemblies.

These six GFE nozzles contained infiltrated tungsten throat inserts fabricated under AFML programs. These programs were conducted by the AVCO Corp., Contract F33615-68-C-1580 and the Aerojet-General Corp., Contract F33615-68-C-1579. These nozzles were supplied by each company as complete assemblies.

The six nozzles were tested under multiple pulse duty cycles on the Aeronutronic 5000-pound thrust solid propellant simulator. The duty cycles were chosen by the Air Force. The simulated propellant was highly aluminized and corrosive. This same propellant was used also in the program for the pyrolytic graphite restart tests.

This report contains a description of the nozzles and test results. Post-test observations have been made, however extensive post-test analyses have not been conducted. These analyses have been conducted on the nozzles by Aerojet and AVCO. These results will be published in their respective programs final reports.

SECTION 2

OBJECTIVE AND SUMMARY

2.1 OBJECTIVE

The objective of these tests were to expose the three Aerojet General nozzles and three AVCO nozzles to several conditions of stop-start operation in an environment consisting of a simulation of ANB-3066 at 5750°F, 18 percent aluminized solid propellant.

2.2 SUMMARY

From January 1969 to September 1969 six silver infiltrated tungsten nozzle assemblies were tested at Philco Ford. All testing was conducted on a 5000-pound thrust solid propellant simulator, utilizing the specified ANB-3066 solid propellant simulation. The six nozzle assemblies tested were subdivided into three groups comprising one AVCO and one Aerojet nozzle assembly in each group. Group I was subjected to one 60-second and two 10-second hot gas test pulses. Group II to one 60-second and two 30-second test pulses and Group III to two 60-second and one 30-second test pulse. A test delay was imposed during the firing modes of each group to cool the tungsten insert prior to retest of each succeeding pulse. All engine performance data and post-test nozzle analysis can be found in the respective test reports located in appendices 1 through 5.

2.2.1 TESTING

The solid propellant simulator used for this program is a slurry-gaseous rocket engine system which reproduces exactly the combustion products and flame temperature of the ANB-3066 solid propellant. Figure 1 presents a test cell schematic of the solid propellant simulator used in the testing series. This simulator system consists of a rocket motor combustion chamber, a rocket motor propellant injector, a propellant feed system and associated controls and instrumentation. The combustion chamber used was an uncooled, silica phenolic lined chamber with an inside diameter of 10 inches and an overall length of 56 inches. The injector used was a water cooled copper injector. The injectants for the specified ANB-3066 simulation were gaseous oxygen, gaseous nitrogen, gaseous hydrogen and the aluminized slurry. Table I presents a percentage breakdown of each gaseous component plus the weight percent of each specie of the aluminized slurry.

During the testing phase of this program a series of pressure and timed interlocks were used in conjunction with the standard facility ignition valve sequence to maintain testing repeatability. The propellant feed system used was also designed to provide a constant mass flow independent of chamber pressure pertibations. From the summary of simulator performance parameters found in Tables A-I through A-VI of Appendices 1 through 5, it is noted that simulator specific and total propellant flow rate plus oxidizer to fuel mixture ratios were held at near constant levels for each nozzle tested.

The test results for each nozzle assembly are tabulated in the test reports, Appendix 1 through 5. A summary of test data comprising actual duty cycle times, initial and final operating chamber pressures and throat diameter changes prior to and at completion of each test pulse, are presented in Table II. A post-test nozzle section depicting the original nozzle profile and the post-test nozzle erosion profile are presented in Figures 2 through 7. A pressure versus time history for each nozzle tested can be found in

Figures A-1 through A-6 of Appendices 1 through 5 and the facility instrumentation list to be used in conjunction with the test cell flow schematic Figure I, can be found in Table III.

2.2.2 OBSERVATIONS

Surface cracking of the tungsten insert was noted on the three Aerojet nozzles. This condition did not occur until well within the restart mode of each test duty cycle. The three AVCO nozzle assemblies did not exhibit surface cracking although they did show some surface erosion.

Extensive graphite erosion occurred after the first test pulse of each nozzle and increased in magnitude with further testing. The erosion was in a bell shape located in the proximity of the insert exit diameter. This condition has been noted before on other test programs where tungsten inserted nozzle assemblies were used and is due partially to the small exit angle used in the exit section of these nozzles.

Shrinkage of the nozzle throat diameter was observed in five of the six nozzle assemblies tested. The Aerojet 2 (AG-2) nozzle exhibited a positive throat radius change of plus 27.5 mils while the other five nozzles decreased from 1.5 mils to 45 mils. The mechanism by which this negative change in area took place is related to compressive plastic flow in the reverse direction brought on by the heating cycle within the nozzle insert. The net result being that the inner half of the tungsten insert wall is in tension, the outer half in compression, causing both the inner and outer insert diameters to decrease.[1]

[1] The Thermochemical Stability of Tungsten Alloys for Restart Applications Final Report. Technical Report AFRPL-TR-68-185, October 1968 K. R. King, K. R. Jawawski, J. R. Bohn, TRW Systems.

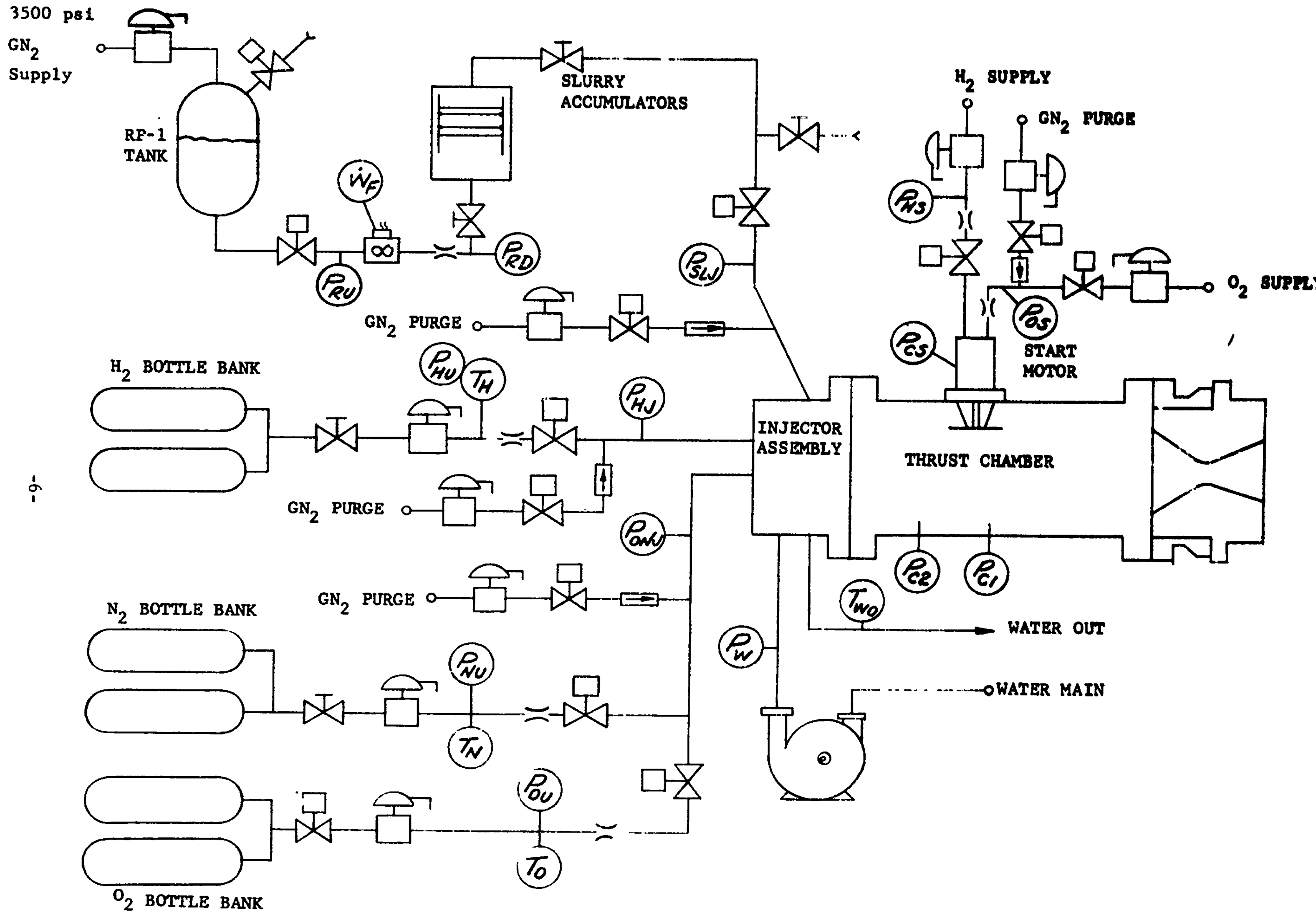
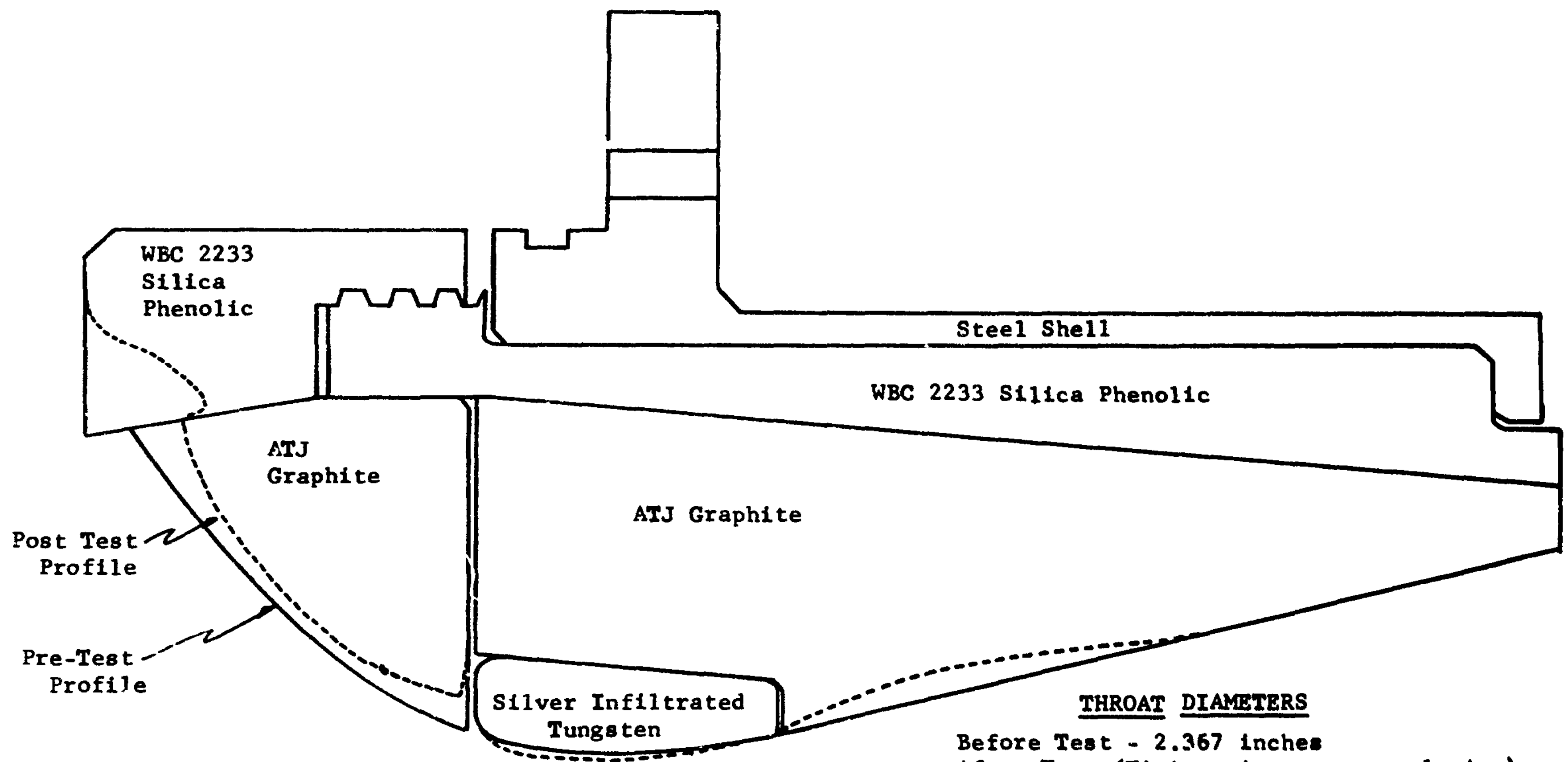


FIGURE 1. TEST CELL C FLOW SCHEMATIC



THROAT DIAMETERS

Before Test - 2.367 inches
After Test (Firing times are cumulative)
30 seconds - 2.335 - 2.343 inches
40 seconds - 2.334 - 2.350 inches
51 seconds - 2.324 - 2.366 inches

Figure 2. POST TEST PROFILE - AEROJET-GENERAL NOZZLE NO. 1

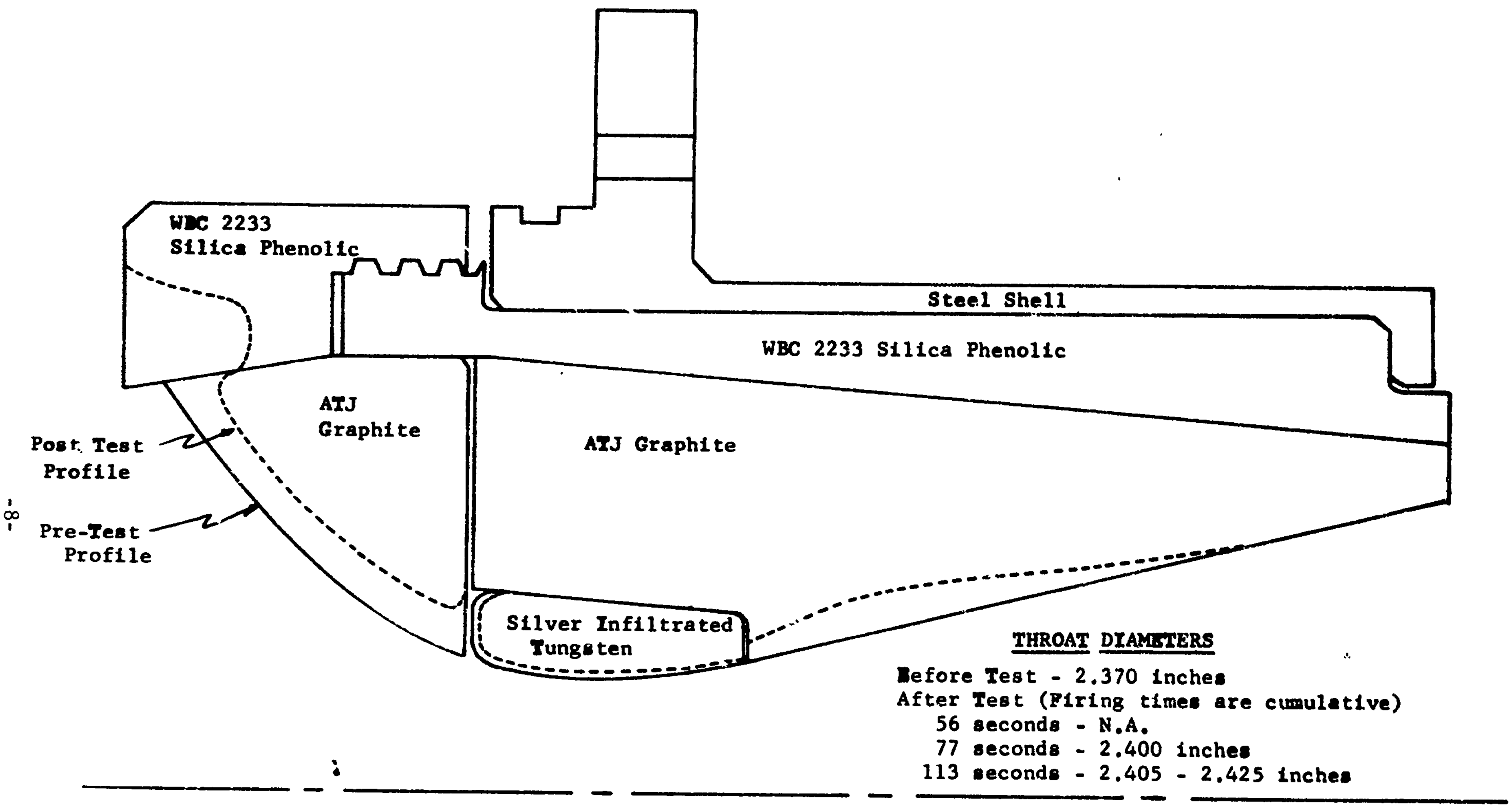


Figure 3. POST TEST PROFILE - AEROJET-GENERAL NOZZLE NO. 2

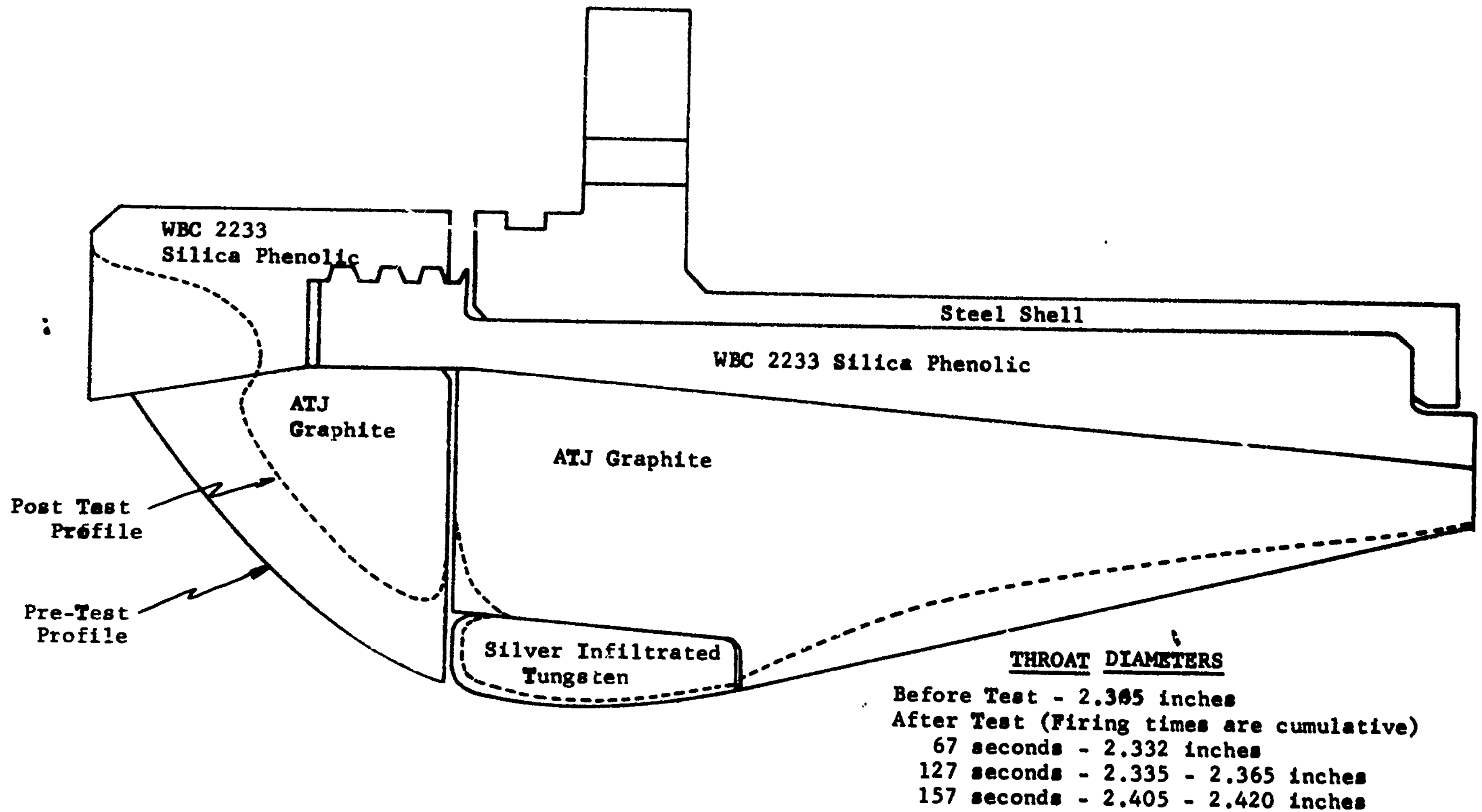


Figure 4. POST TEST PROFILE - AEROJET-GENERAL NOZZLE NO. 3

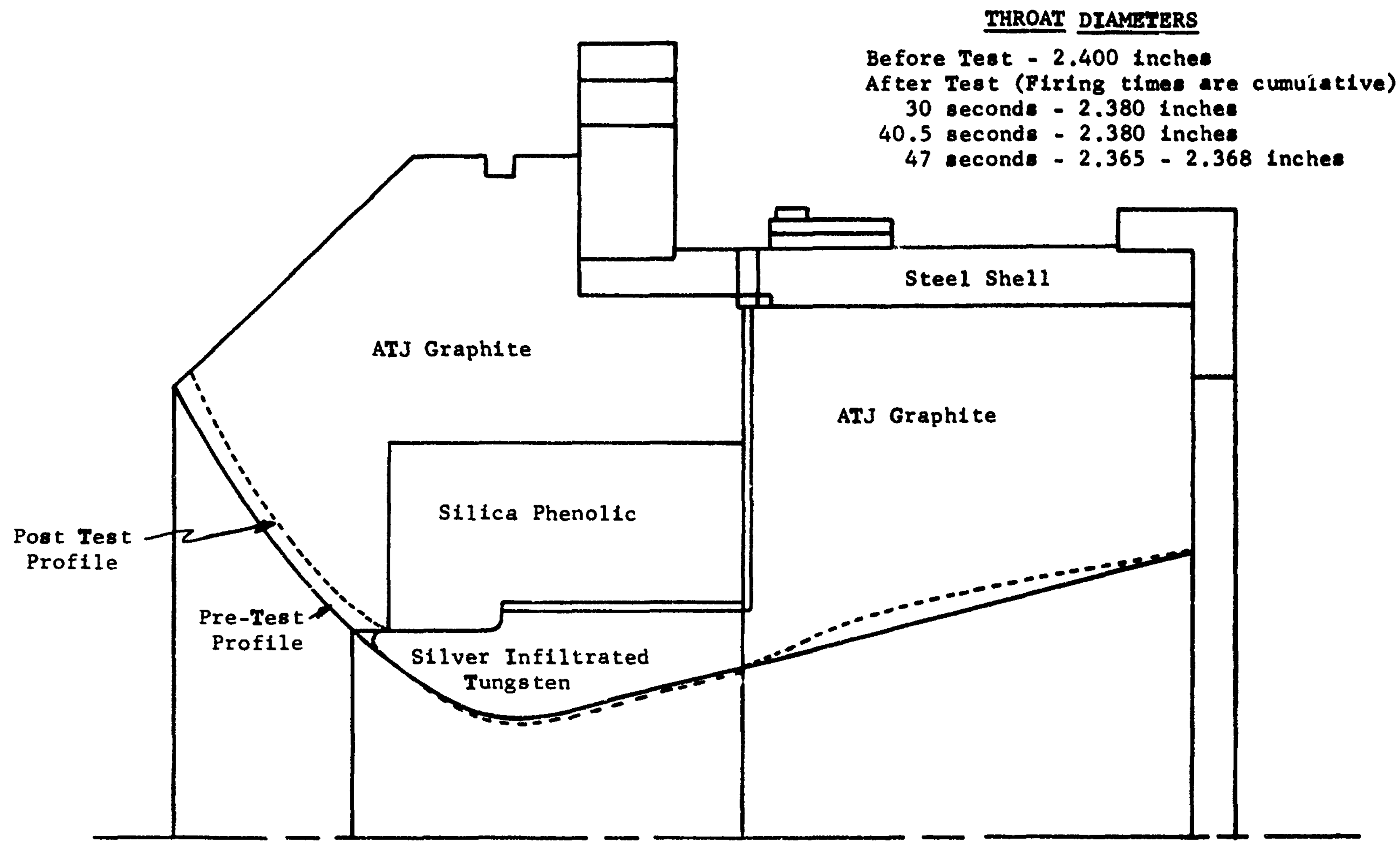


Figure 5. POST TEST PROFILE - AVCO NOZZLE NO. 1

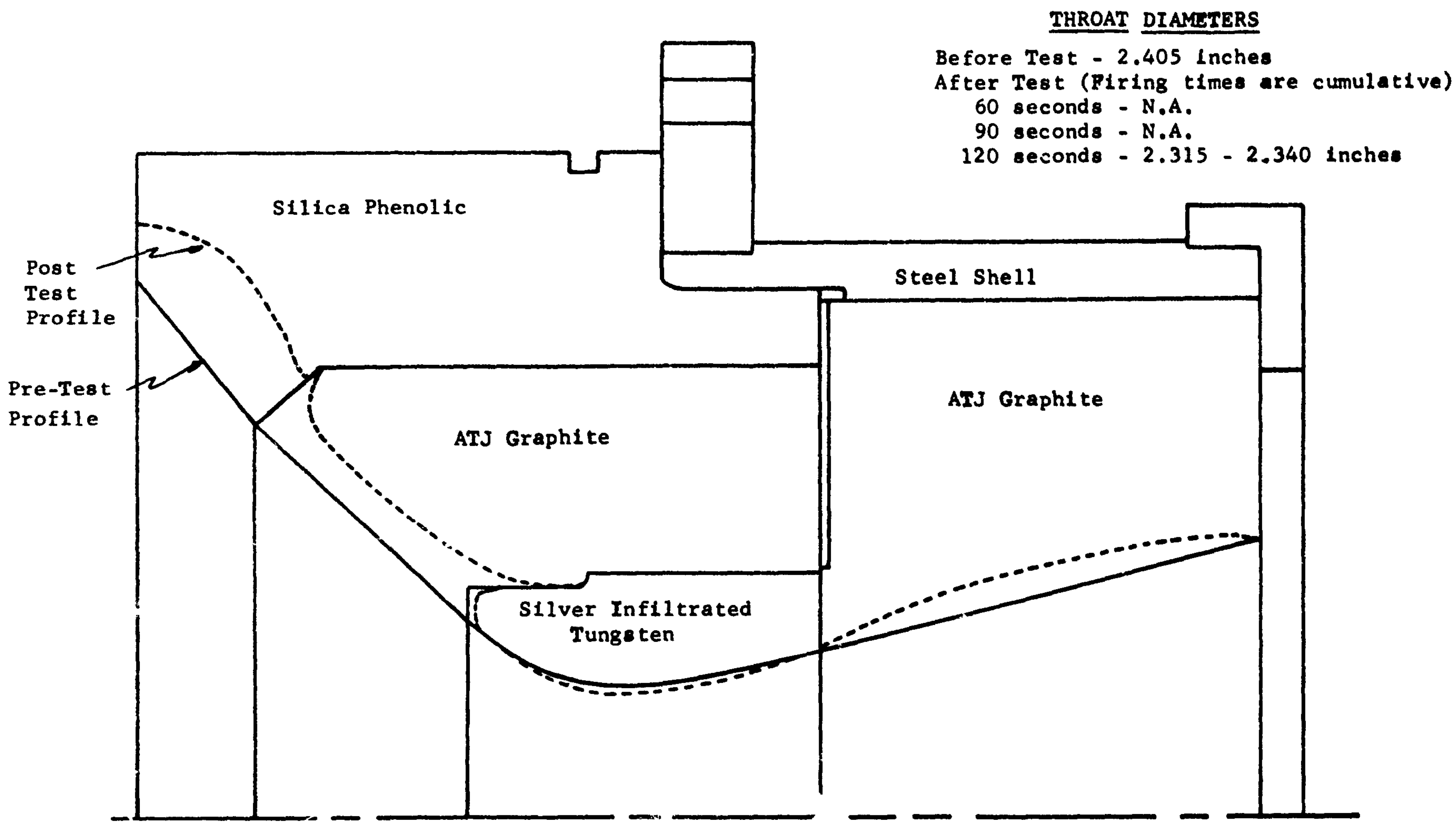


Figure 6. POST TEST PROFILE - AVCO NOZZLE NO. 2

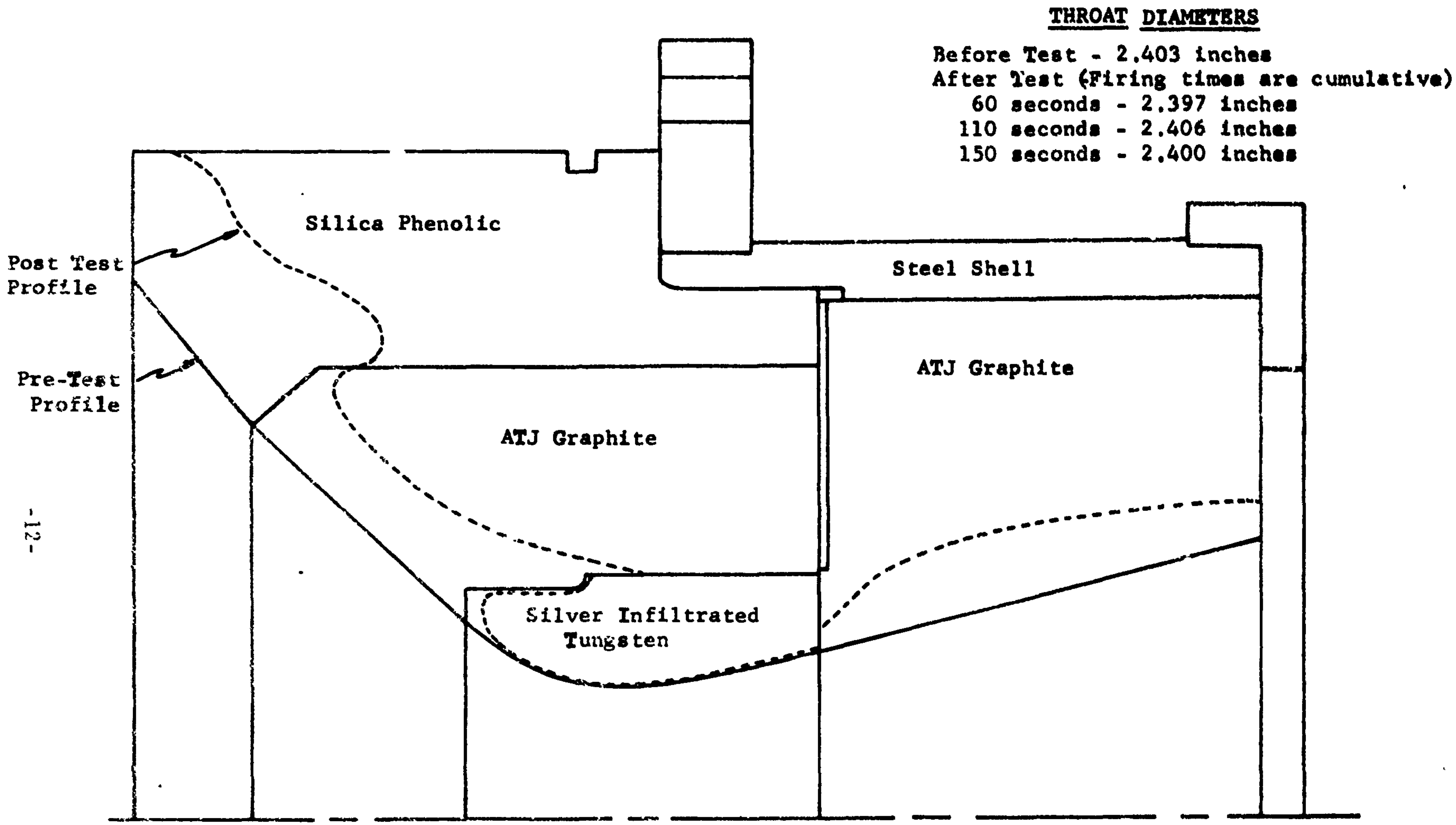


Figure 7. POST TEST PROFILE - AVCO NOZZLE NO. 3

TABLE I

ANB-3066 (MINUTEMAN WING VI, STAGE 2) SOLID PROPELLANT SIMULATION

The simulation constituents are as follows:

Slurry Components	Formula	Weight Percent
Trichloroethane	$C_2H_3Cl_3$	29.09
RP-1	$CH_{1.953}$	4.90
Aluminum powder	Al	10.79
Aluminum oxide	Al_2O_3	7.86
Napalm soap	$C_{18}H_{35}Al\ O_5$	0.71
Total Slurry		53.35 %
Gaseous oxygen		35.54
Gaseous nitrogen		8.71
Gaseous hydrogen		2.40
Total		100.00 %

The simulation theoretical flame temperature is 5750°F at 700 psia pressure. The theoretical C* value is 5212 ft/sec.

TABLE II

SUMMARY OF TEST DATA

NOZZLE	TEST TYPE	DUTY CYCLE, (SEC) THEORETICAL	DUTY CYCLE, (SEC) ACTUAL	INITIAL OPERATING CHAMBER PRESSURE, P_C (PSIA)	FINAL CHAMBER PRESSURE, P_C (PSIA)	THROAT DIAMETERS, D_t (IN) BEFORE	THROAT DIAMETERS, D_t (IN) AFTER	CHANGE IN THROAT RADIUS, Δr (MILS)
Aerojet-1	GROUP I	30 10 10	30 10½ 10½	770	780 780 780	2.367	2.335-2.343 2.334-2.350 2.324-2.366	-12 to -16 -8½ to -16½ -½ to -21½
AVCO-1	GROUP I	30 10 10	30 10½ 6½	700	710 715 725	2.40	2.380 2.380 2.365-2.368	-10 -10 -16 to -17½
Aerojet-2	GROUP II	60 30 30	56 21 36	740	740 710 700	2.370	N.A. 2.400 2.405-2.425	- +15 +17½ to +27½
AVCO-2	GROUP II	60 30 30	60 30 30	700	720 710 715	2.405	N.A. N.A. 2.315-2.340	- - -32½ to -45
Aerojet-3	GROUP III	60 60 30	5½ 61 60 30	740	765 765 715	2.365	2.332 2.335-2.365 2.405-2.420	-16½ 0 to -15 +20 to +27½
AVCO-3	GROUP III	60 60 30	60 50 40	700	720 700 680	2.403	2.397 2.406 2.40	-3 +1½ -1½

TABLE III

RESTART NOZZLE TEST PROGRAM - 5K SIMULATOR

INSTRUMENTATION LIST

Symbol	Description	Range	Presentation*	Nominal Value
P_{C1}	Simulator chamber press	0-750 psig	A - D - M	700 psig
P_{C2}	Simulator chamber press	0-1000 psig	A - D	700 psig
P_{CS}	Start motor chamber press	0-1500 psig	A - D - S	800 psig
P_{OS}	Oxygen system pressure (start motor)	0-1500 psig	-	1250 psig
P_{HS}	Hydrogen system pressure (start motor)	0-1500 psig	-	1250 psig
P_{ONJ}	O_2-N_2 injection pressure	0-1500 psig	A - D	900 psig
P_{HJ}	Hydrogen injection pressure	0-1500 psig	A - D	850 psig
P_{SLJ}	Slurry injection pressure	0-1500 psig	A - D - M	1050 psig
P_{RU}	RP-1 pressure U/S venturi	0-2500 psig	A - D	1750 psig
P_{OU}	O_2 pressure U/S nozzle	0-2000 psig	A - D	1450 psig
P_{NU}	N_2 pressure U/S nozzle	0-1500 psig	A - D	1450 psig
P_{HU}	H_2 pressure U/S nozzle	0-1500 psig	A - D	1250 psig
P_W	Coolant water inlet press	0-300 psig	A - S	300 psig
$\dot{W}_F$	Fuel flowmeter		A - D - M	700 cps
T_{WO}	Injector coolant outlet temperature	0-500°F	A - M	100°F
T_O	Oxygen system temperature	0-500°F	D	ambient
T_N	Nitrogen system temperature	0-500°F	D	ambient
T_H	Hydrogen system temperature	0-500°F	D	ambient
SW_S	Start motor pressure interlock	0-1000 psig	A	500 psig
S_W	Main motor ignition press interlock	0-300 psig	A	185 psig
SW_M	Main motor combustion pressure interlock	0-1000psig	A	400 psig

*Legend: A - Oscillograph
D - Digital
M - Meter
S - Strip chart

APPENDIX-1

TEST REPORT

AEROJET NOZZLE (AG-1)

JANUARY 23 AND 29, 1969

INTRODUCTION

The Aerojet-General Corporation nozzle assembly with a silver infiltrated tungsten nozzle insert (designated AG-1) was tested on the Aeronutronic 5K solid propellant exhaust hot gas simulator at the El Toro test site in January 1969 as a part of Contract F04611-69-C-0039.

SUMMARY

The AG-1 nozzle assembly was tested for a total of 51 seconds in conjunction with the 5K solid propellant simulator at a chamber pressure of about 780 psia. The test duty cycle consisted of a 30-second pulse and two 10.5-second pulses initiated after allowing the nozzle insert to cool down below 400°F. The simulation utilized was the ANB-3066 solid propellant. The silver infiltrated tungsten nozzle insert did not exhibit any degration or cracking until the final 10-second pulse which resulted in two carcks in the throat insert piece.

Throughout the duty cycle the 5K solid propellant simulator performed satisfactorily. The simulator parameters of propellant flow rate, mixture ratio and thrust chamber pressure were maintained at near constant levels to impart a constant test environment for the AG nozzle assembly.

DISCUSSION

Testing of the Aerojet-General Corporation silver infiltrated tungsten nozzle insert assembly was conducted at the El Toro test site on the Aeronutronic 5K solid propellant exhaust hot gas simulator. The nozzle assembly (designated AG-1) was installed on the simulator and exposed to the initial 30-second duration test pulse A on 23 January 1969. After a cool down of the nozzle insert to below 400°F (which was attained approximately 1½ hours after the initial test pulse)the second test pulse was attempted but was terminated by the cell instrumentation automatic shutdown circuitry. This test attempt exposed the nozzle to an environment of

the simulator gas propellants for a duration of 1.9 seconds at a chamber pressure of about 350 psia. Post-test examination revealed that the slurry fuel had partially clogged the rocket motor injector holes. This malfunction required an overhaul of the rocket motor assembly, thereby delaying the completion of the nozzle test duty cycle.

Testing was resumed and completed on 29 January. Completion of the duty cycle consisted of two 10.5-second test pulses with a 1½ hour delay between testing. The test delay was necessary to accomplish an adequate post-test cool down of the tungsten nozzle insert to below 400°F.

The nozzle insert measured 2.367 inches diameter prior to testing. After the first 30-second test pulse (while the insert was still warm) the insert throat diameter was slightly elliptical measuring 2.349 inches on the horizontal axis and 2.355 inches on the verical axis. The horizontal axis coincided with the nozzle thermocouple ports. After complete cool down to ambient temperature the throat diameter measured 2.335 on the horizontal axis and 2.343 on the vertical axis.

Between test pulse B and C (while the insert was still warm) the throat diameter was measured at 2.334 on the horizontal axis and 2.350 on the vertical axis. Post-test inspection of the nozzle assembly after test pulse C revealed two cracks in the insert. When measured at ambient temperatures the diameter at the major crack was 2.324 inches and the complementary diameter was 2.366 inches.

The nozzle exit cone was slightly eroded to a bell shape in the proximity of insert exit diameter. The insert entrance phenolic piece had eroded about 0.3 inches over its entire surface - the part measured 3.54 inches diameter at the nozzle insert entrance. The phenomenon of the insert entrance and the exit cones erosion was noted after the first 30-second pulse and increased in magnitude with testing.

Figure A-1 presents the chamber pressure versus time curve for the complete duty cycle. The chamber pressure remained at near 780 psia throughout the duty cycle; the oxidizer/fuel propellant misture ratio was maintained at 0.62 as compared to a theoretical value of 0.638. Table A-I presents a tabulation of the solid propellant simulator performance parameters for the three test pulses. The simulator specific and total propellant flow rates and the oxidizer/fuel mixture ratio were maintained at almost constant levels throughout each test pulse and were closely matched from pulse to pulse. The chamber pressure variation was less than 10 psi from high to low throughout the duty cycle. Table I presents the components of the ANB-3066 solid propellant simulation which is computed to deliver the exact exhaust product species and heat of formation as the solid propellant.

Based upon the data presented in Figure A-1 and Table A-I it has been concluded that the AG-1 nozzle was exposed satisfactorily to the required test performance conditions. The nozzle assembly was returned to Aerojet-General, Sacramento, via GBL on 12 February 1969.

EDWARDS AFB-RPL RESTART NOZZLE TEST PROGRAM
AEROJET GENERAL AG-1 SILVER INFILTRATED TUNGSTEN NOZZLE ASSEMBLY
CHAMBER PRESSURE VERSUS TIME DUTY CYCLE
5000 LB THRUST LEVEL
CONTRACT F04611-69-C-0039

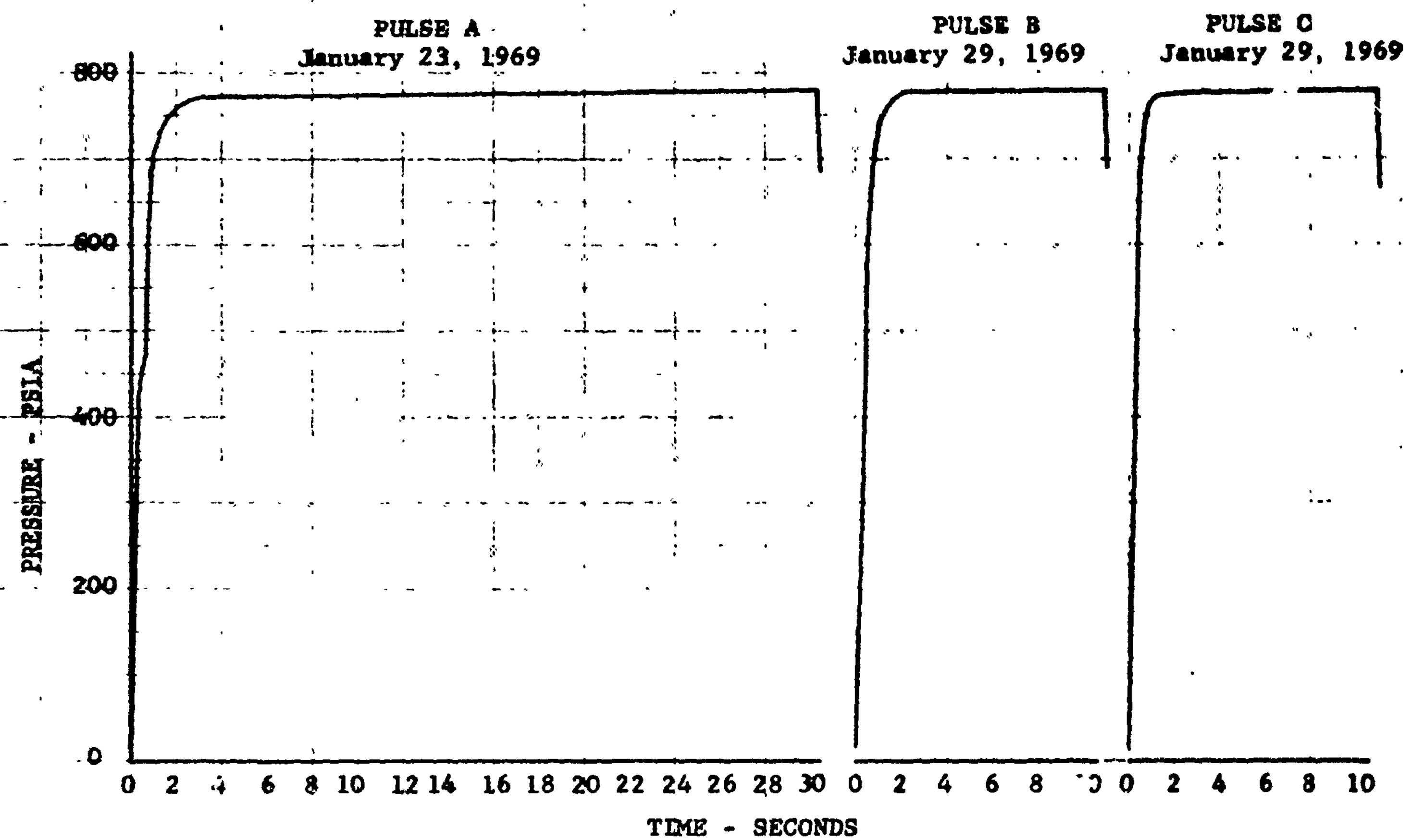


Figure A-1

TABLE A-I

SUMMARY OF SOLID PROPELLANT SIMULATOR PERFORMANCE PARAMETERS
AG-1 NOZZLE ASSEMBLY

	PULSE DURATION (sec)	CHAMBER PRESSURE (psia)	NOZZLE INSERT DIA. (in.)	TOTAL PROPELLANT FLOWRATE (lb/sec)	SLURRY FLOWRATE (lb/sec) & %	OXYGEN FLOWRATE (lb/sec) & %	NITROGEN FLOWRATE (lb/sec) & %	HYDROGEN FLOWRATE (lb/sec) & %	CALCULATED C* (ft/sec)	CALC. C* EFF. %[1]	OXIDIZER/ FUEL MIXTURE RATIO[2]
Desired Theoretical Values				21.50	11.46 53.35%	7.65 35.54%	1.87 8.71%	0.52 2.40%	5212	100.0	.638
Pulse A-Start of test		776	2.367	21.79	11.79 54.0%	7.61 35.0%	1.87 8.6%	0.52 2.4%	5040	96.7	.618
Pulse A-End of test	29.8	783	2.349- 2.355	21.92	11.79 53.8%	7.69 35.1%	1.92 8.7%	0.52 2.4%	4995	95.8	.625
Pulse B-Start of test		776	2.335- 2.343	21.53	11.68 54.1%	7.51 34.9%	1.82 8.5%	0.52 2.4%	4985	95.6	.615
Pulse B-End of test	10.5	778	2.334- 2.350	21.58	11.68 54.0%	7.56 35.1%	1.82 8.5%	0.52 2.4%	5000	95.9	.619
Pulse C (Constant parameters)	10.5	774	2.334- 2.350 (start)	21.54	11.64 54.0%	7.54 35.1%	1.84 8.5%	0.52 2.4%	4980 (start)	95.5	.620

Note:

(1) The calculated C* values do not take into account any chamber pressure increase caused by the additional flow of the silica phenolic liner material ablation during the test pulse.

(2) Oxygen flowrate divided by the sum of the slurry and hydrogen flowrates.

APPENDIX-2

TEST REPORT

AEROJET NOZZLE (AG-2)

APRIL 3 AND 14, 1969

INTRODUCTION

The Aerojet-General Corporation nozzle assembly with a silver infiltrated tungsten nozzle insert (designed AG-2) was tested on the Aeronutronic 5K solid propellant exhaust hot gas simulator at the El Toro test site in April 1969 as a part of Contract F04611-69-C-0039.

SUMMARY

The AG-2 nozzle assembly was tested for a total of 113 seconds in conjunction with the 5K solid propellant simulator at a chamber pressure ranging from about 750 to 700 psia. The test duty cycle consisted of a 56-second pulse, a 21-second pulse and a final 36-second pulse. The 56-second and 21-second pulses were run consecutively with an elapsed time of about 7 minutes between pulses. The final 36-second pulse was run several days afterward. The simulation utilized was the ANB-3066 solid propellant.

After the second test pulse, the upper half of the silver infiltrated tungsten nozzle insert exhibited widespread surface pitting and minute, shallow cracks at the nozzle entrance in that same area. After the final test pulse the surface pitting was more pronounced, also, material undercutting had occurred in the area of the incipient cracks. The lower portion of the nozzle exhibited some shallow erosion streaks.

Throughout the duty cycle the 5K solid propellant simulator performed satisfactorily. The simulator parameters of propellant flow rate, mixture ratio and thrust chamber pressure were maintained at near constant levels to impart a constant test environment for the AG nozzle assembly.

DISCUSSION

Testing of the Aerojet-General Corporation silver infiltrated tungsten nozzle insert assembly was conducted at the El Toro test site on the Aeronutronic 5K solid propellant exhaust hot gas simulator. The nozzle

assembly (designated AG-2) was installed on the simulator and exposed to the initial 56-second duration test pulse A and 21-second test pulse B on 3 April 1969. The elapsed time between test pulses was about 7 minutes. The initial chamber pressure of test pulse A was 747 psia which slightly decreased, then increased to a pressure of 753 psia at test end. The initial chamber pressure of test pulse B was 740 psia which steadily decreased to 724 psia.

Due to a leakage of slurry propellant from a fuel accumulator feed line that occurred after test pulse B the test sequence was not completed on that date. Examination of the silica phenolic liner material in the thrust chamber indicated that a new liner assembly would be required before proceeding with the test sequence. Test cell cleanup and liner procurement delayed the final test pulse until 14 April. On that date a 36-second duration run was accomplished with the AG-2 nozzle assembly. The initial chamber pressure was 713 psia which gradually decreased to 698 psia at test end.

The nozzle insert measured 2.370 inches diameter prior to testing. After test pulse B the upper half of the nozzle insert exhibited widespread surface pitting (about .03 inch deep) and minute, shallow cracks at the nozzle entrance in that area. The nozzle insert throat diameter was 2.400 inches irrespective of the pitting.

After the final test pulse the surface pitting was more pronounced (up to .06 inch deep). Also, material undercutting had occurred in the area of the incipient cracks. The lower portion of the nozzle exhibited some shallow erosion streaks. The entire surface of the nozzle insert was rough and uneven - the throat diameter measured between 2.405 and 2.425 inches, irrespective of the pitting.

The nozzle exit cone was unevenly eroded to a bell shape in the proximity of the insert exit diameter. The insert entrance graphite piece had eroded

such that the part measured 4.0 inches diameter at the nozzle insert entrance and about 8.5 inches diameter at the leading edge. One large crack and several minor cracks were noted. The entrance and exit cone erosion increased between test pulse B and C.

Figure A-2 presents the chamber pressure versus time curve for the complete duty cycle. The chamber pressure initially was near 750 psia decreasing to 700 psia near the conclusion of the duty cycle; the oxidizer/fuel propellant mixutre ratio was maintained between 0.63 and 0.64 as compared to a thoeretical value of 0.638. Table A-II presents a tabulation of the solid propellant simulator performance parameters for the three test pulses. The simulator specific and total propellant flow rates and the oxidizer/fuel mixture ratio were maintained at almost constant levels throughout each test pulse and were closely matched from pulse to pulse. The chamber pressure decrease was attributable to the nozzle insert erosion throughout the duty cycle. Table I presents the components of the ANB-3066 solid propellant simulation which is computed to deliver the exact exhaust product species and heat of formation as the solid propellant.

Based upon the data presented in Figure A-2 and Table A-II it has been concluded that the AG-2 nozzle was exposed satisfactorily to the required test performance conditions. The nozzle assembly was returned to Aerojet-General, Sacramento, via GBL on 2 May 1969.

EDWARDS AFB-RPL RESTART NOZZLE TEST PROGRAM
AEROJET GENERAL AG-2 SILVER INFILTRATED TUNGSTEN NOZZLE ASSEMBLY
CHAMBER PRESSURE VERSUS TIME DUTY CYCLE
5000 LB THRUST LEVEL
CONTRACT F04611-69-C-0039

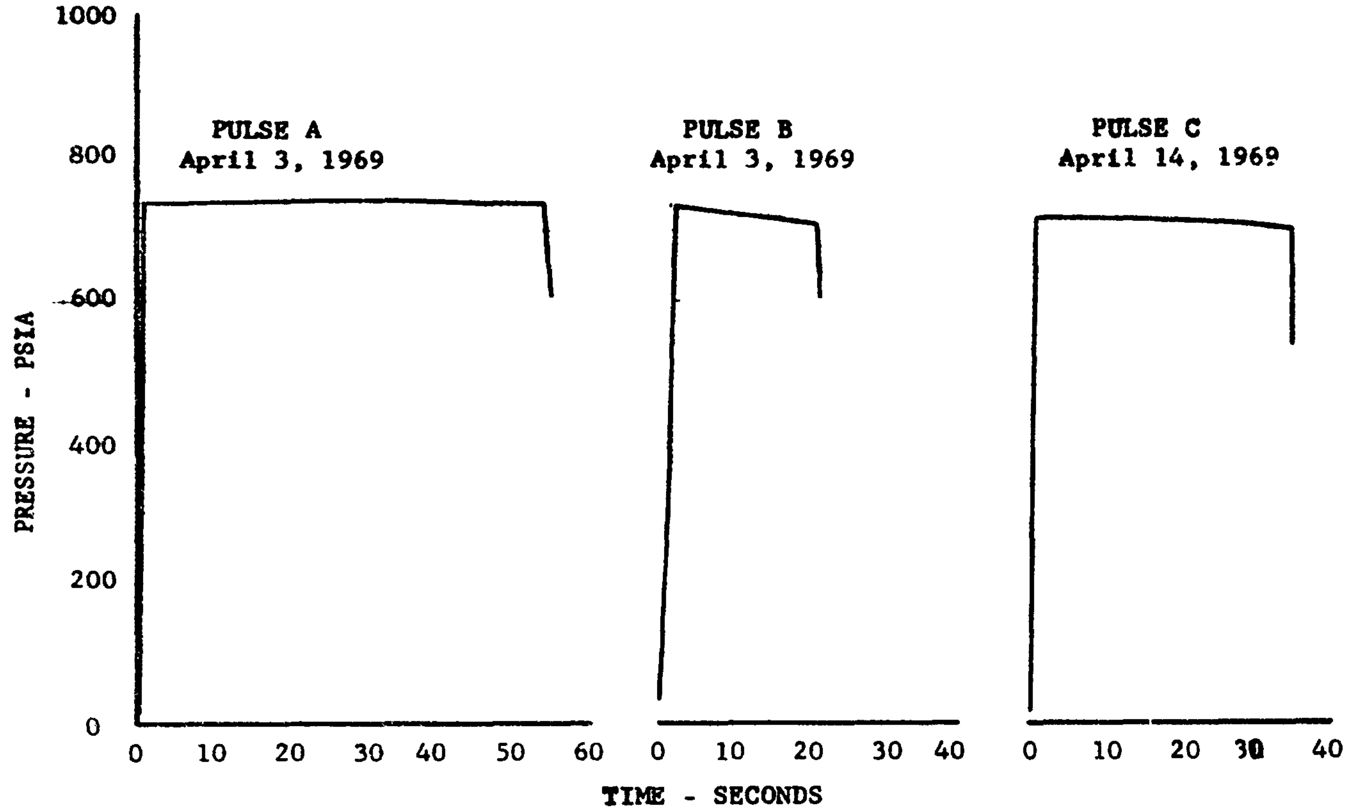


Figure A-2

TABLE A-II

SUMMARY OF SOLID PROPELLANT SIMULATOR PERFORMANCE PARAMETERS
AG-2 NOZZLE ASSEMBLY

	PULSE DURATION (sec)	CHAMBER PRESSURE (psia)	NOZZLE INSERT DIA. (in)	TOTAL PROPELLANT FLOWRATE (lb/sec)	SLURRY FLOWRATE (lb/sec) & %	OXYGEN FLOW RATE (lb/sec) & %	NITROGEN FLOW RATE (lb/sec) & %	HYDROGEN FLOW RATE (lb/sec) & %	CALCULATED C* (ft/sec)	CALC.(1) C* EFF. %	OXIDIZER/(2) FUEL MIXTURE RATIO
Desired Theoretical Values				20.80	11.09 53.35%	7.40 35.54%	1.81 8.71%	0.50 2.40%	5212	100.0	.638
Pulse A-Start of test		747	2.370	20.74	11.12 53.6 %	7.27 35.1 %	1.87 9.0 %	0.48 2.3 %	5110	98.0	.627
Pulse A-End of test	56.1	753	-	21.05	11.17 53.1 %	7.47 35.5 %	1.92 9.1 %	0.49 2.3 %	-	-	.640
Pulse B-Start of test	21.1	740	-	20.76	11.15 53.7%	7.33 35.3 %	1.79 8.6 %	0.49 2.4 %	5075 (end)	97.4	.631
Pulse C-Start of Test		713	2.400	20.63	11.04 53.5 %	7.30 35.4 %	1.81 8.8 %	0.48 2.3 %	5030	96.5	.634
Pulse C-End of test	35.9	698	2.415 (avg)	20.79	11.07 53.2 %	7.39 35.5 %	1.84 8.9 %	0.49 2.4 %	4950	95.0	.639

Note:

(1) The calculated C* values do not take into account any chamber pressure increase caused by the additional flow of the silica phenolic liner material ablation during the test pulse.

(2) Oxygen flowrate divided by the sum of the slurry and hydrogen flowrates.

APPENDIX-3

TEST REPORT

AEROJET NOZZLE (AG-3)

AUGUST 5-SEPTEMBER 11 AND 17, 1969

INTRODUCTION

The Aerojet-General Corporation nozzle assembly with a silver infiltrated tungsten nozzle insert (designated AG-3) was tested on the Aeronutronic 5K solid propellant exhaust hot gas simulator at the El Toro test site in August and September 1969 as a part of Contract F04611-69-C-0039.

SUMMARY

The AG-3 nozzle assembly was tested for a total of 156.5 seconds in conjunction with the 5K solid propellant simulator at a chamber pressure ranging from about 750 psia up to 770 psiaaand then to 718 psia at the conclusion of the duty cycle. The test duty cycle consisted of a 5.5-second pulse, which resulted due to an erroneous test abort, a 61-second pulse, a 60-second pulse and a final 30-second test pulse. The tungsten nozzle throat insert was at ambient temperature conditions at the start of every test pulse. The simulation utilized was the ANB-3066 solid propellant.

A major crack in the silver infiltrated tungsten nozzle insert was noted after the 61-second test pulse B. At the conclusion of testing additional minor cracks and an area of rough erosion were also noted on the insert surface.

Throughout the duty cycle the 5K solid propellant simulator performed satisfactorily. The simulator parameters of propellant flow rate, mixture ratio and thrust chamber pressure were maintained at near constant levels to impart a constant test environment for the AG nozzle assembly.

DISCUSSION

Testing of the Aerojet-General Corporation silver infiltrated tungsten nozzle insert assembly was conducted at the El Toro test site on the Aeronutronic 5K solid propellant exhaust hot gas simulator. The nozzle assembly (designated AG-3) was installed on the simulator and exposed to a

5.5-second and a 61-second test pulse on 5 August 1969. The first test pulse was erroneously aborted. The chamber pressure reached 742 psia during this segment. After cool down the nozzle was exposed to the full duration 61-second test pulse B. The initial chamber pressure was 748 psia which increased to a maximum of 759 psia and was 765 psia at test end. Testing was terminated following this test pulse due to internal water coolant passage leakage detected in the simulator propellant injector. After a new injector was fabricated and installed testing was resumed.

Test pulse C was conducted on 11 September 1969 and ran for the scheduled 60-second duration. The initial chamber pressure was 762 psia which increased to a maximum of 770 psia and was 757 psia at test end.

Test Pulse D was conducted on 17 September 1969 and ran for the scheduled 30-second duration. The initial chamber pressure was 729 psia which increased to a maximum of 738 psia and was 718 psia at test end.

The pre-test nozzle throat diameter measured 2.365 inches. After the first days' testing on 5 August 1969 a major crack was noted in the nozzle throat insert. The throat diameter was measured at 2.332 inches. After test pulse C on the nozzle throat diameter measured between 2.335 inches and 2.365 inches with the average diameter at 2.358 inches. Some rough surface erosion in an area of 60° arc was noted after this test pulse. After the final test pulse the throat diameter measured between 2.405 inches and 2.420 inches. The major crack experienced by the nozzle throat insert extended radially from the throat surface at approximately 12 o'clock position as the nozzle was installed in the simulator. The nozzle successfully survived the final two test pulses totaling 90 seconds after the crack was noted. The area of rough erosion was centered at the 1:30 o'clock position looking forward. After the final test some lesser cracks near the area of rough erosion were also noted. In addition, the nozzle exit cone was unevenly eroded to a bell shape in the proximity of the insert exit diameter.

Figure A-3 presents the chamber pressure versus time curve for the complete duty cycle. The chamber pressure initially was near 750 psia increasing to 770 psia then to 718 psia at the conclusion of the duty cycle. The ignition pulse over approximately the first 3 seconds of the test represents the hump in the curves. The initial chamber pressures reported are after ignition had been turned off. Table A-III presents a tabulation of the solid propellant simulator performance parameters for the four test pulses. The simulator specific and total propellant flow rates and the oxidizer/fuel mixture ratic were maintained at almost constant levels throughout each test pulse and were closely matched from pulse to pulse. Table I presents the components of the ANB-3066 solid propellant simulation which is computed to deliver the exact exhaust product species and heat of formation as the solid propellant.

CONCLUSION

Based upon the data presented in Figure A-3 and Table III it has been concluded that the AG-3 nozzle was exposed satisfactorily to the required test performance conditions. The nozzle assembly was returned to Aerojet-General, Sacramento, via GBL on 3 October 1969.

EDWARDS AFB-RPL RESTART NOZZLE PROGRAM
AEROJET GENERAL AG -3 SILVER INFILTRATED TUNSTEN NOZZLE ASSEMBLY
CHAMBER PRESSURE VERSUS TIME DUTY CYCLE
5000 LB THRUST LEVEL
CONTRACT F04611-69-C-0039

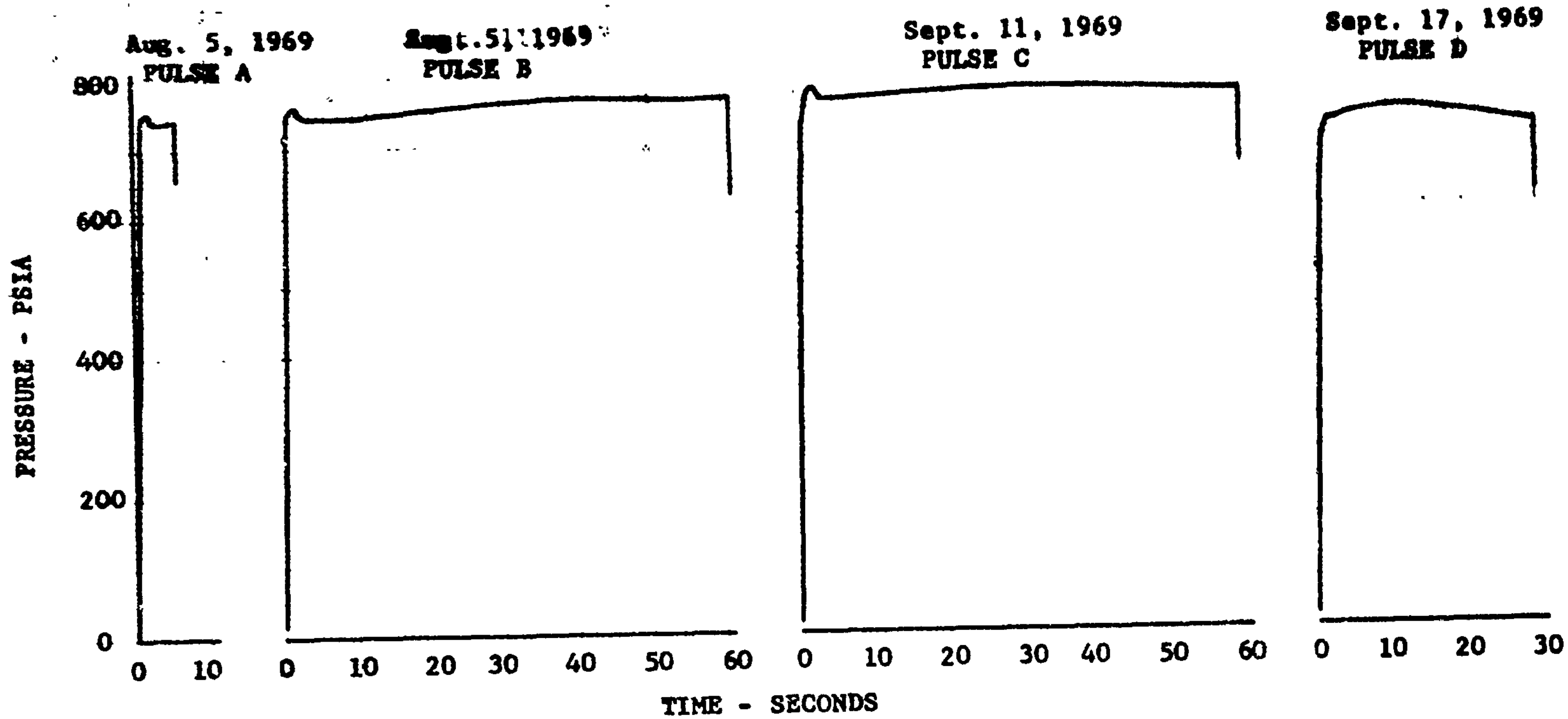


Figure A-3

TABLE A-III

SUMMARY OF SOLID PROPELLANT SIMULATOR PERFORMANCE PARAMETERS
AG -3 NOZZLE ASSEMBLY

	PULSE DURATION (sec)	CHAMBER PRESSURE (psia)	NOZZLE INSERT DIA. (in.)	TOTAL PROPELLANT FLOWRATE (lb/sec)	SLURRY FLOWRATE (lb/sec) & %	OXYGEN FLOW RATE (lb/sec) & %	NITROGEN FLOW RATE (lb/sec) & %	HYDROGEN FLOW RATE (lb/sec) & %	CALCULATED C* (ft/sec)	CALC.(1) C* EFF. %	OXIDIZER/(2) FUEL MIXTURE RATIO
Desired Theoretical Values				20.80	11.44 55.0%	7.05 33.9%	1.81 8.7%	0.50 2.4%	5212	100.0	0.590
Pulse A	5.5	742	2.365	20.69	11.53 55.8%	6.94 33.5%	1.76 8.5%	0.46 2.2%	5070	97.3	0.579
Pulse B-Start of test		748	2.365	20.80	11.57 55.6%	7.02 33.8%	1.75 8.4%	0.46 2.2%	5080	97.5	0.592
Pulse B-End of test	61.0	765	2.332	21.02	11.58 55.0%	7.14 34.0%	1.81 8.6%	0.49 2.4%	5000	95.9	0.592
Pulse C-Start of test		762	2.332	20.85	11.47 55.0%	7.11 34.1%	1.79 8.6%	0.48 2.3%	5020	96.3	0.595
Pulse C-End of test	60.0	757	2.358	21.08	11.50 54.5%	7.24 34.4%	1.85 8.8%	0.49 2.3%	5045	96.8	0.604
Pulse D-Start of test		723	2.358	20.70	11.42 55.2%	7.06 34.1%	1.83 8.8%	0.39 1.9%	4950	95.0	0.598
Pulse D-End of test	30.0	718	2.412	20.80	11.42 55.0%	7.13 34.2%	1.86 8.9%	0.39 1.9%	5075	97.4	0.604

Note:

(1) The calculated C* values do not take into account any chamber pressure increase caused by the additional flow of the silica phenolic liner material ablation during the test pulse.

(2) Oxygen flowrate divided by the sum of the slurry and hydrogen flowrates.

APPENDIX-4

TEST REPORT

AVCO NOZZLE (AV-1)

FEBRUARY 20, 1969

INTRODUCTION

The AVCO Corporation nozzle assembly with a silver infiltrated tungsten nozzle insert (designated AV-1) was tested on the Aeronutronic 5K solid propellant exhaust hot gas simulator at the El Toro test site on 20 February 1969 as part of contract F04 611-69-C-0039.

SUMMARY

The AVCO nozzle assembly was tested for a total of 47 seconds in conjunction with the 5K solid propellant simulator at a chamber pressure of about 715 psia. The test duty cycle consisted of a 30-second pulse, a 10.5-second pulse and a 6.6 second pulse. The restart test pulses were initiated after allowing the nozzle insert to cool down below 200°F. The simulation utilized was the ANB-3066 solid propellant. The silver infiltrated tungsten nozzle insert did not exhibit any degradation or cracking during the duty cycle.

Throughout the duty cycle the 5K solid propellant simulator performed satisfactorily. The simulator parameters of propellant flow rate, mixture ratio and thrust chamber pressure were maintained at near constant levels to impart a constant test environment for the AVCO nozzle assembly.

DISCUSSION

Testing of the AVCO Corporation silver infiltrated tungsten nozzle insert assembly was conducted at the El Toro test site on the Aeronutronic 5K solid propellant exhaust hot gas simulator. The nozzle assembly (designated AV-1) was installed on the simulator and exposed to the simulator environment on 20 February 1969. A test duty cycle of 30 seconds on, two hours off; 10.5 seconds on, one hour off; and 6.6 seconds on was imposed on the nozzle assembly. The nozzle insert temperatures measured approximately 150°F before pulse B and approximately 200°F before pulse C.

Test pulse A ran for the scheduled 30.2-second duration with chamber pressure recording 702 psia at the test start and 713 psia at test end.

Test pulse B ran for the scheduled 10.5-second duration with the chamber pressure recording 708 psia at the test start and 716 at test end.

The nozzle insert measured 2.400 inches diameter prior to testing. After the first 30-second test pulse (while the insert was still warm) the insert throat diameter measured 2.380 inches. Between test pulse B and C (while the insert was still warm) the throat diameter was measured at 2.380 inches. At the completion of the duty cycle the nozzle insert throat was measured at 2.365 and 2.368 inches on complementary axes. Post-test inspection revealed no visible degradation or cracks on the nozzle insert.

Test pulse C was terminated by the test engineer at 6.6 seconds into the schedule 10.5 second duration run when the visual gauge monitoring the simulator thrust chamber pressure recorded a sudden drop in pressure to about 400 psia. The simulator thrust chamber pressure is redundantly monitored with two other transducer readings on the oscillograph and diital acquisition system. These other readouts did not corroborate the drop in chamber pressure recorded by the particular transducer output monitored on the visual gauge. The thrust chamber pressure, as recorded by these two transducers, indicated that pressure was maintained at the 720 psia level and the test could have continued to the scheduled duration. Post-test analysis of the hardware revealed that during the test a slight leak had developed on the chamber pressure transducer port which caused that plumbing line to the transducer to plug with condensed exhaust particles and caused a low pressure recording. For future testing the visual gauge thrust chamber pressure monitor will record from a chamber transducer located in a less sensitive area of the chamber.

Figure A-4 presents the chamber pressure versus time curve for the complete duty cycle. The chamber pressure remained at near 715 psia throughout the duty cycle; the oxidizer/fuel propellant mixture ratio was maintained at 0.615 as compared to a theoretical value of 0.638.

Table A-IV presents a tabulation of the solid propellant simulator performance parameters for the three test pulses. It was noted that the simulator specific and total propellant flow rates and the oxidizer/fuel mixture ratio were maintained almost constant throughout each test pulse and were closely matched from pulse to pulse. The chamber pressure variation was within 20 psi from high to low throughout the duty cycle. Table II presents the components of the ANB-3066 solid propellant simulation which is computed to deliver the exact exhaust product species and heat of formation as the solid propellant.

Upon post-test disassembly of the facility aft closure from the nozzle a cylindrical portion of the nozzle graphite inlet remained with the aft closure. Examination of the crack of surface showed some rust discoloration. This indicated that the crack was present prior to removal of the aft closure.

Based upon the data presented in Figure A-4 and Table IV it has been concluded that the AV-1 nozzle was exposed satisfactorily to the required test performance conditions. It is planned to ship the nozzle assembly to AVCO Corporation, Lowell, Massachusetts via GBL air freight by 28 February 1969.

EDWARDS AFB-RPL RESTART NOZZLE TEST PROGRAM
AVCO AV-1 SILVER INFILTRATED TUNGSTEN NOZZLE ASSEMBLY
CHAMBER PRESSURE VERSUS TIME DUTY CYCLE
February 20, 1969
5000 LB THRUST LEVEL
CONTRACT F04 611-68-C-0039

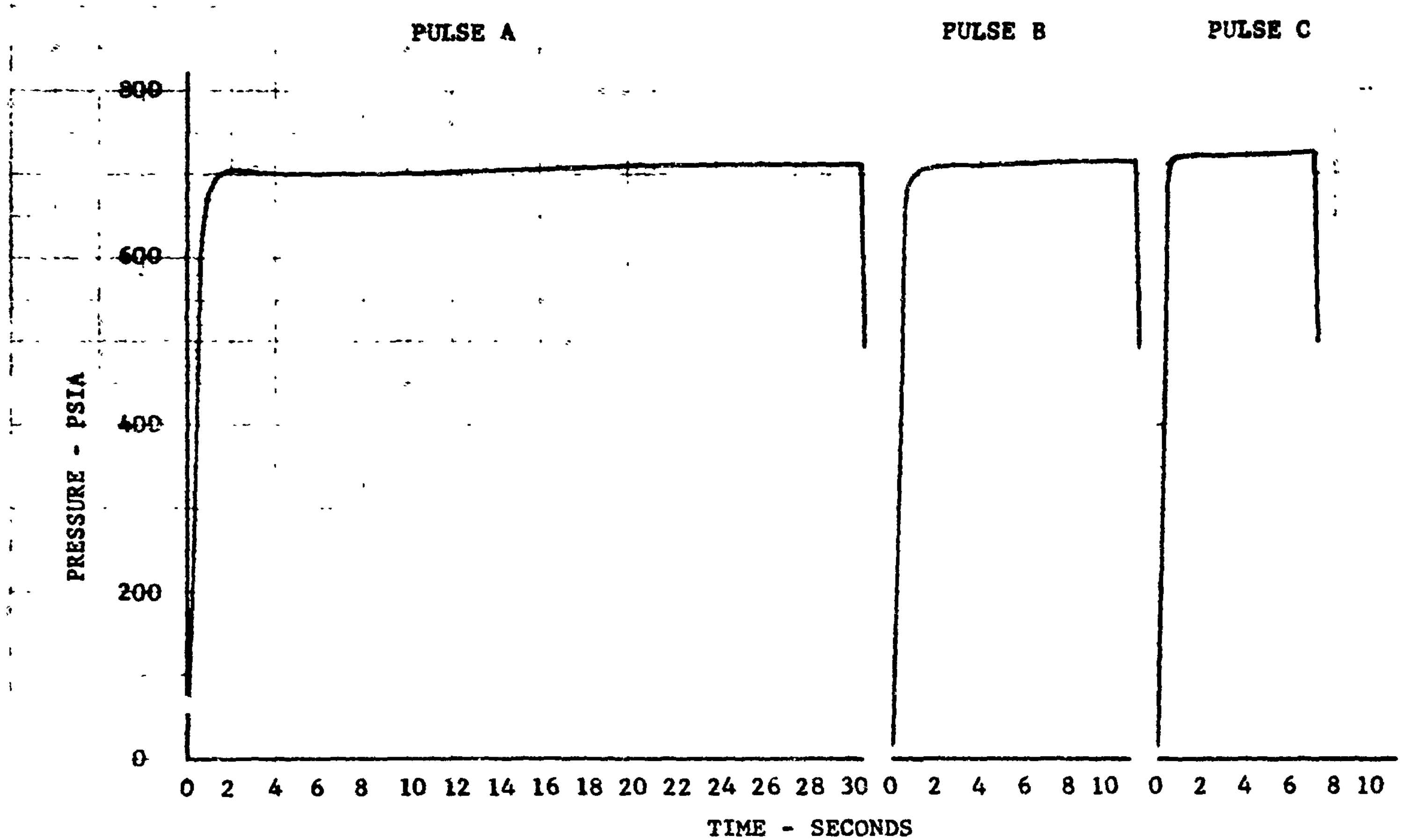


FIGURE A-4

TABLE A-IV

SUMMARY OF SOLID PROPELLANT SIMULATOR PERFORMANCE PARAMETERS
AV-1 NOZZLE ASSEMBLY

	PULSE DURATION (sec)	CHAMBER PRESSURE (psia)	NOZZLE INSERT DIA. (in.)	TOTAL PROPELLANT FLOWRATE (lb/sec)	SLURRY FLOWRATE (lb/sec) & %	OXYGEN FLOWRATE (lb/sec) & %	NITROGEN FLOWRATE (lb/sec) & %	HYDROGEN FLOWRATE (lb/sec) & %	CALCULATED C* (ft/sec)	CALC. C* EFF. %	OXIDIZER/(1) FUEL MIXTURE RATIO
Desired Theoretical Values				21.50	11.46 53.35%	7.65 35.54%	1.87 8.71%	0.52 2.40%	5212	100.0	.638
Pulse A-Start of test		702	2.400	21.42	11.64 54.4%	7.48 34.8%	1.79 8.4%	0.51 2.4%	4768	91.5	.615
Pulse A-End of test	30.2	713	2.380	21.55	11.64 54.0%	7.58 35.1%	1.82 8.5%	0.51 2.4%	4733	90.7	.624
Pulse B	10.5	716 (end)	2.380	21.31	11.61 54.5%	7.39 34.6%	1.80 8.5%	0.51 2.4%	4808 (end)	92.1	.609
Pulse C-Start of test		720	2.380	21.41	11.64 54.4%	7.45 34.8%	1.80 8.4%	0.52 2.4%	4814	92.2	.613
Pulse C-End of test	6.6	725	2.365- 2.368	21.41	11.64 54.4%	7.45 34.8%	1.80 8.4%	0.52 2.4%	4800	92.0	.613

Note:
(1) Oxygen flowrate divided by the sum of the slurry and hydrogen flowrates.

APPENDIX-5

TEST REPORT

AVCO NOZZLE (AV-2 AND AV-3)

SEPTEMBER 17 AND 22, 1969

INTRODUCTION

Two AVCO Corporation nozzle assemblies with silver infiltrated tungsten nozzle inserts (designated AV-2 and AV-3) were tested on the Aeronutronic 5K solid propellant exhaust hot gas simulator at the El Toro test site in September 1969 as a part of Contract F04611-69-C-0039.

SUMMARY

Two AVCO Corporation nozzle assemblies were tested in conjunction with the 5K solid propellant simulator. The first nozzle (designated AV-2) was tested for a total of 120 seconds. The test duty cycle consisted of a 60-second and two 30-second test pulses. The restart test pulses occurred with the nozzle throat insert surface temperature at 350°F for test pulse B and 550°F for test pulse C. The simulator chamber pressure ranged between 700 and 720 psia throughout the duty cycle.

The second nozzle (designaged AV-3) was tested for a total of 150 seconds. The test duty cycle consisted of a 60-second, a 50-second and a final 40-second test pulse. The 50-second test pulse was initiated with the nozzle throat insert surface temperature at about 310°F. The other test pulses were initiated with the nozzle at ambient temperature. The simulator chamber pressure ranged from about 695 to 715 psia throughout the duty cycle. the higherpressures occurring during the first test pulse.

When examined at the conclusion of the test series the two tungsten nozzle throat inserts did not exhibit any surface cracks but exhibited some surface roughness and erosion.

Throughout the duty cycle the 5K solid propellant simulator performed satisfactorily. The simulator parameters of propellant flow rate, mixture ratio and thrust chamber pressure were maintained at near constant levels.to impart a constant test environment for the AVCO nozzle assemblies.

DISCUSSION

Testing of the AVCO Corporation silver infiltrated tungsten nozzle insert assemblies was conducted at the El Toro test site on the Aeronutronic 5K solid propellant exhaust hot gas imulator. The nozzle assemblies were tested in the order requested by AVCO personnel. The nozzle assembly designated AV-2 was installed on the simulator and exposed to the scheduled 60-second and two 30-second test pulses on 17 September 1969. The elapsed time between test pulses was approximately one and one-half hours.

The initial chamber pressure of test pulse A was 698 psia which increased during the test to a high of 720 psia at shutdown. The test pulse duration was 59.8 seconds. The initial chamber pressure of test pulse B was 709 psia which remained constant throughout the test. The test pulse duration was 30.1 seconds. The initial chamber pressure of test pulse C was 702 psia which increased to 712 psia at test end. The test pulse C duration was 30.0 seconds. Test pulses B and C were initiated while the nozzle throat insert surface was warm, measuring 350°F immediately prior to test pulse B and 550°F immediately prior to test pulse C.

At the conclusion of the testing cycle the nozz throat insert exhibited no cracks but some surface erosion. The nozzle insert throat measured 2.405 inches diameter prior to testing and measured between 2.315 and 2.340 inches diameter after the final test pulse.

The nozzle assembly designated AV-3 was exposed to the scheduled 60-second, 50-second and final 40-second test pulses on 22 September 1969. The elapsed time between test pulse A and B was approximately one and one-half hours and was approximately three hours between test pulse B and C.

The inital chamber pressure of test pulse A was 709 psia which increased to about 715 psia at test end. The test pulse duration was 59.9 seconds. The initial chamber pressure of test pulse B was 696 psia which increased

to 700 psia. The test pulse duration was 49.8 seconds. The test pulse C chamber pressure remained near constant at 695 psia. The final test pulse duration was 40.0 seconds. The nozzle throat insert surface measured 310°F immediately prior to test pulse B. The insert surface was at ambient temperature prior to test pulse C.

At the conclusion of the testing cycles, the nozzle throat insert exhibited no cracks but some surface erosion. The nozzle insert throat measured 2.403 inches diameter prior to testing and was 2.397 inches diameter prior to test pulse B; 2.406 inches diameter prior to test pulse C and 2.400 inches diameter after the final test pulse.

Figures A-5 and A-6 present the chamber pressure versus time curves for the complete duty cycle of the AV-2 and AV-3 tests respectively. The ignition pulse over approximately the first 3 seconds of the test represents the hump in the curves. The initial chamber pressures reported are after ignition has been turned off. Tables A-V and A-VI present the tabulation of the solid propellant simulator performance parameters of each test pulse of the AV-2 and AV-3 tests, respectively. The simulator specific and total propellant flow rates and the oxidizer/fuel mixture ratio were maintained at almost constant levels throughout each test pulse and were closely matched from pulse to pulse. Table I presents the components of the ANB-3066 solid propellant simulation which is computed to deliver the exact exhaust product species and heat of formation as the solid propellant.

CONCLUSION

Based upon the data presented in Figures A-5 and A-6, Tables A-V and A-VI it has been concluded that the AV-2 and -3 nozzles were exposed satisfactorily to the required test performance conditions. The nozzle assemblies were returned to AVCO Corporation, Lowell, Massachusetts via GBL on 3 October 1969.

EDWARDS AFB-RPL RESTART NOZZLE TEST PROGRAM
AVCO CORP. AV-2 SILVER INFILTRATED TUNGSTEN NOZZLE ASSEMBLY
CHAMBER PRESSURE VERSUS TIME DUTY CYCLE
5000 LB THRUST LEVEL
CONTRACT F04611-69-C-0039
TEST DATE: 17 September 1969

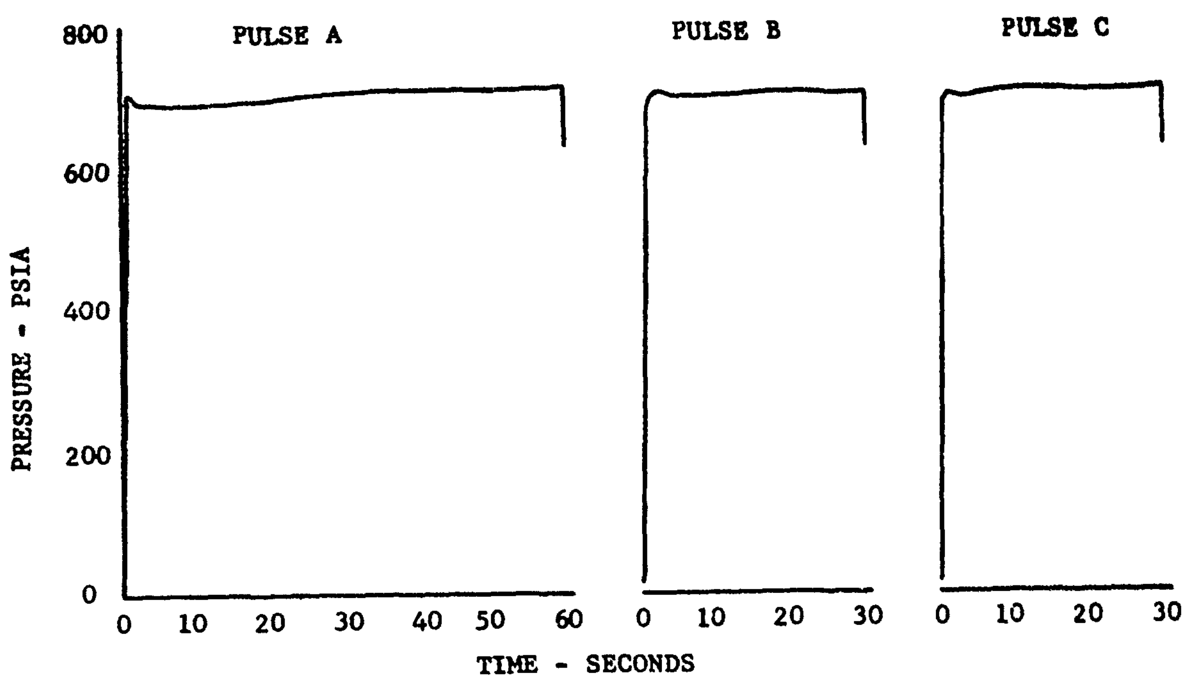


Figure A-5

EDWARDS AFB-RPL RESTART NOZZLE TEST PROGRAM
AVCO CORP. AV-3 SILVER INFILTRATED TUNSTEN NOZZLE ASSEMBLY
CHAMBER PRESSURE VERSUS TIME DUTY CYCLE
5000 LB THRUST LEVEL
CONTRACT F04611-69-C-0039
TEST DATE: 22 September 1969

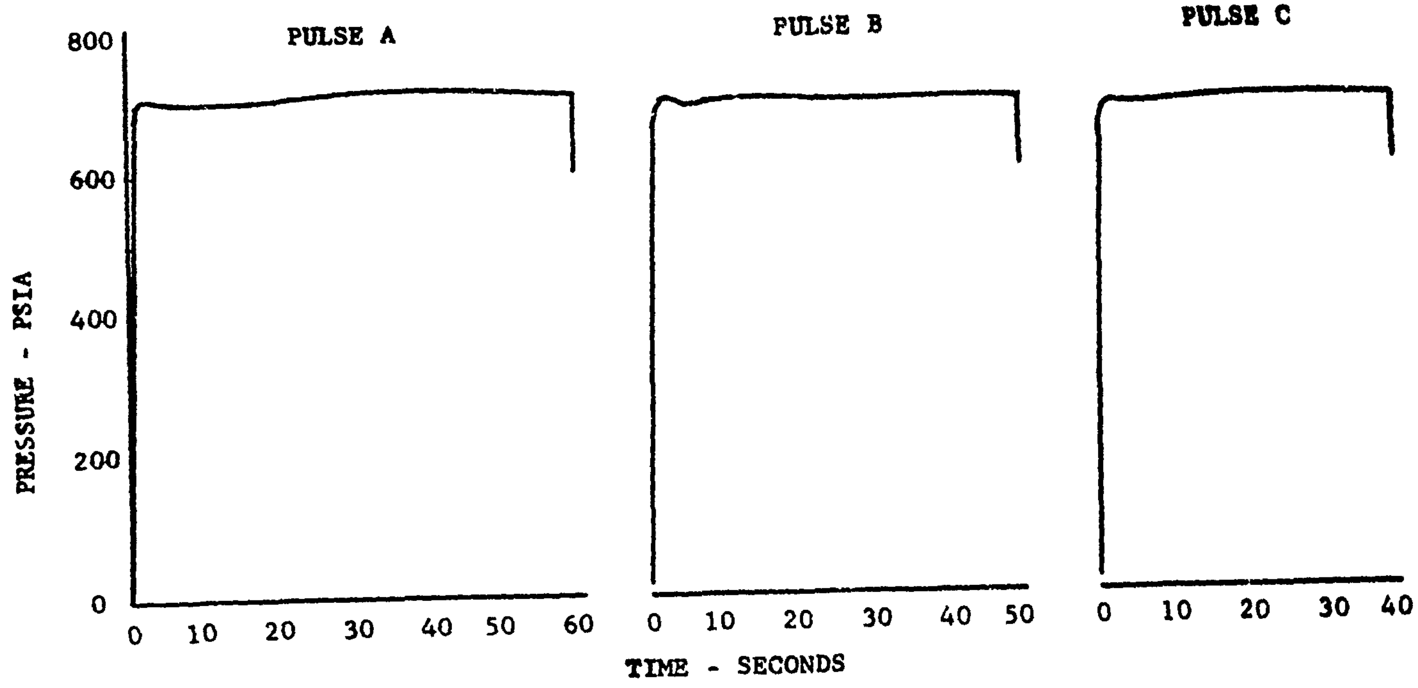


Figure A-6

TABLE A-V

SUMMARY OF SOLID PROPELLANT SIMULATOR PERFORMANCE PARAMETERS
AV-2 NOZZLE ASSEMBLY

	PULSE DURATION (sec)	CHAMBER PRESSURE (psia)	NOZZLE INSERT DIA. (in.)	TOTAL PROPELLANT FLOWRATE (lb/sec)	SLURRY FLOWRATE (lb/sec) & %	OXYGEN FLOW RATE (lb/sec) & %	NITROGEN FLOW RATE (lb/sec) & %	HYDROGEN FLOW RATE (lb/sec) & %	CALCULATED C* (ft/sec)	CALC.[1] C* EFF. %	OXIDIZER/[2] FUEL MIXTURE RATIO
Desired Theoretical Values				20.70	11.56 55.9%	6.95 33.5%	1.80 8.7%	0.39 1.9%	5212	100.0	0.580
Pulse A-Start of test		698	2.405	20.50	11.45 55.9%	6.86 33.4%	1.81 8.8%	0.38 1.9%	4975	95.5	0.580
Pulse A-End of test	59.8	720	-	20.66	11.45 55.5%	6.96 33.6%	1.86 9.0%	0.39 1.9%	-	-	0.588
Pulse B-Start of test		709	-	20.44	1.42 55.9%	6.83 33.4%	1.81 8.8%	0.38 1.9%	-	-	0.579
Pulse B-End of test	30.1	709	-	20.53	11.42 55.7%	6.89 33.5%	1.84 8.9%	0.38 1.9%	-	-	0.584
Pulse C-Start of test		702	-	20.39	11.48 56.3%	6.74 33.1%	1.78 8.7%	0.39 1.9%	-	-	0.568
Pulse C-End of test	30.0	712	2.330	20.52	11.48 56.0%	6.85 33.4%	1.80 8.7%	0.39 1.9%	4760	91.3	0.577

Note:

(1) The calculated C* values do not take into account any chamber pressure increase caused by the additional flow of the silica phenolic liner material ablation during the test pulse.

(2) Oxygen flowrate divided by the sum of the slurry and hydrogen flowrates.

TABLE A-VI

SUMMARY OF SOLID PROPELLANT SIMULATOR PERFORMANCE PARAMETERS
AV-3 NOZZLE ASSEMBLY

	PULSE DURATION (sec)	CHAMBER PRESSURE (psia)	NOZZLE INSERT DIA. (in.)	TOTAL PROPELLANT FLOWRATE (lb/sec)	SLURRY FLOWRATE (lb/sec)	OXYGEN FLOW RATE (lb/sec)	NITROGEN FLOW RATE (lb/sec)	HYDROGEN FLOW RATE (lb/sec)	CALCU-LATED C* (ft/sec)	CALC.(1) C* EFF.	OXIDIZER/(2) FUEL MIXTURE RATIO
Desired Theoretical Values				20.70	11.56 55.9%	6.95 33.5%	1.80 8.7%	0.39 1.9%	5212	100.0	0.580
Pulse A-Start of test		709	2.403	20.52	11.50 56.0%	6.83 33.3%	1.81 8.8%	0.38 1.9%	5040	96.7	0.575
Pulse A-End of test	59.9	714	2.397	20.88	11.57 55.4%	7.01 33.6%	1.91 9.1%	0.39 1.9%	4965	95.3	0.586
Pulse B-Start of test		696	2.397	20.47	11.50 56.1%	6.81 33.3%	1.79 8.8%	0.37 1.8%	4935	94.7	0.574
Pulse B-End of test	49.8	700	2.406	20.68	11.53 55.8%	6.93 33.5%	1.83 8.8%	0.39 1.9%	4950	95.0	0.581
Pulse C-Start of test		693	2.406	20.40	11.45 56.1%	6.75 33.1%	1.81 8.9%	0.39 1.9%	4970	95.4	0.570
Pulse C-End of test	40.0	695	2.400	20.61	11.47 55.6%	6.92 33.6%	1.83 8.9%	0.39 1.9%	4910	94.2	0.583

Note:
(1) The calculated C* values do not take into account any chamber pressure increase caused by the additional flow of the silica phenolic liner material ablation during the test pulse.

(2) Oxygen flowrate divided by the sum of the slurry and hydrogen flowrates.